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Procedia Structural Integrity 13 (2018) 2221–2226

Structural Integrity Procedia

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ECF22 - Loading and Environmental effects on Structural Integrity

Microstructural and fracture analysis of microalloyed steel weld metal

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Abstract

In this paper is presented behavior of microalloyed steel weld metal with niobium during impact testing, as well as microstructural characterization. Impact tests were done on instrumented Charpy pendulum at room temperature, at -40^{0}C and -55^{0}C. At room temperature, crack propagation energy is much higher than crack initiation energy, while at -40^{0}C and -55^{0}C crack growth energy is lower than crack initiation energy. Fractographic investigation of the fracture surfaces has shown that at room temperature ductile trans-granular fracture is dominant, with a small amount of brittle trans-granular fracture. At lower temperature, the share of brittle fracture is increased, and inter-granular brittle fracture becomes dominant.

Peer-review under responsibility of the ECF22 organizers.

Keywords: weld metal; micro-alloyed steel; microstructures; fracture analysis; toughness

1. Introduction

Finegrain microalloyed steels have wide field of application in various industries because of their very good mechanical properties. These properties are result of chemical composition and the processing technology that are closely related to the microstructure. Low carbon content provides them to be welded easily without preheating. In the structure of weld metal, besides other microconstituents, is very often present acicular ferrite, which has a positive effect on toughness. Acicular ferrite nucleates within the original austenite grains on inclusions that have complex

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Peer-review under responsibility of the ECF22 organizers.
10.1016/j.prostr.2018.12.137

composition. The size of these inclusions is in the range of 0.25 to 0.80 microns by J.M.Wang et al. (2015) and D.M.Liang et al. (2011). Ti and Nb in microalloyed steels create inclusions which inhibit the growth of the original austenite grain boundaries and induce nucleation of acicular ferrite, which has a positive effect on the fracture toughness by W.Yan et al. (2016). Instrumented Charpy pendulum enables separation of total impact energy (E_u) into crack initiation energy (E_i) and crack propagation energy (E_p). The result is the possibility of more accurate assessment material toughness by R.Prokić Cvetković et al. (2006). For practical application of welded joints, the crack growth energy is crucial, because the possibility of crack existence in welded joints should not be excluded by R.Prokić Cvetković et al. (2006).

Nomenclature

E_u	total impact energy
E_i	crack initiation energy
E_p	crack propagation energy
AF	acicular ferrite
PF	proeutectoid ferrite
FS	ferrite with secondary phase
GB	upper bainite
F	force
D_f	deflection
T	temperature

2. Experimental procedure

In this experiment were used hot rolled plates of ferrite-pearlite micro-alloyed steel with Nb (thickness of these plates is 11 mm). The chemical compositions of base material and filler material are given in Table 1. Mechanical properties of both materials are given in Table 2. Electrode wire denoted as VAC60Ni (made by Jesenice, Slovenia) ∅1,2mm (as filler material) and shielding atmosphere Ar+5% CO_2+0,91% O_2 were used. Such a shielding atmosphere provides good arc stability and good spilling of filler material, without spattering. The wire is alloyed with Ni, designed for welding of unalloyed and alloyed steels, with guaranteed mechanical properties at low temperatures.

Table 1. Chemical compositions of base material and filler material.

	Chemical composition, %									
element	C	Si	Mn	P	S	Cu	Al	Nb	Ti	Cr	Ni
steel	0.07	0.15	0.66	0.016	0.010	0.13	0.092	0.077	-	0.042	0.036
Electrode wire	0.08-0.10	0.70-0.85	1.40-1.60	<0.025	<0.025	-	-	-	-	-	1.00-1.20

Table 2. Mechanical properties of base material and filler material

	Re, [N/mm^2]	Rm, [N/mm^2]	A_5, [%]	KV(20°C), [J]
steel	448-456	543-551	33-34	129-156
Electrode wire	440-510	560-630	22-30	80-125; 30-35 (at -40°C)

Coupon plates with V grooves were welded, with one root pass and three filler passes, with heat input of 7 kJ/cm. Welding was performed without preheating thanks to the low content of carbon and manganese.

3. Results and discussion

Microstructural analysis of the weld metal showed the presence of acicular ferrite (AF), of pro-eutectoid ferrite (PF), a ferrite with secondary phase (FS), and upper bainite (GB) in the subsequent heated zones between passes (Figure 1). Pro-eutectoid ferrite and ferrite with secondary phase are separated by original austenite grain boundaries, while the acicular ferrite is within the original austenite grains. Amount of acicular ferrite is significantly higher than other microconstituents. The microstructure of acicular ferrite has much better toughness than all previously mentioned microstructures.

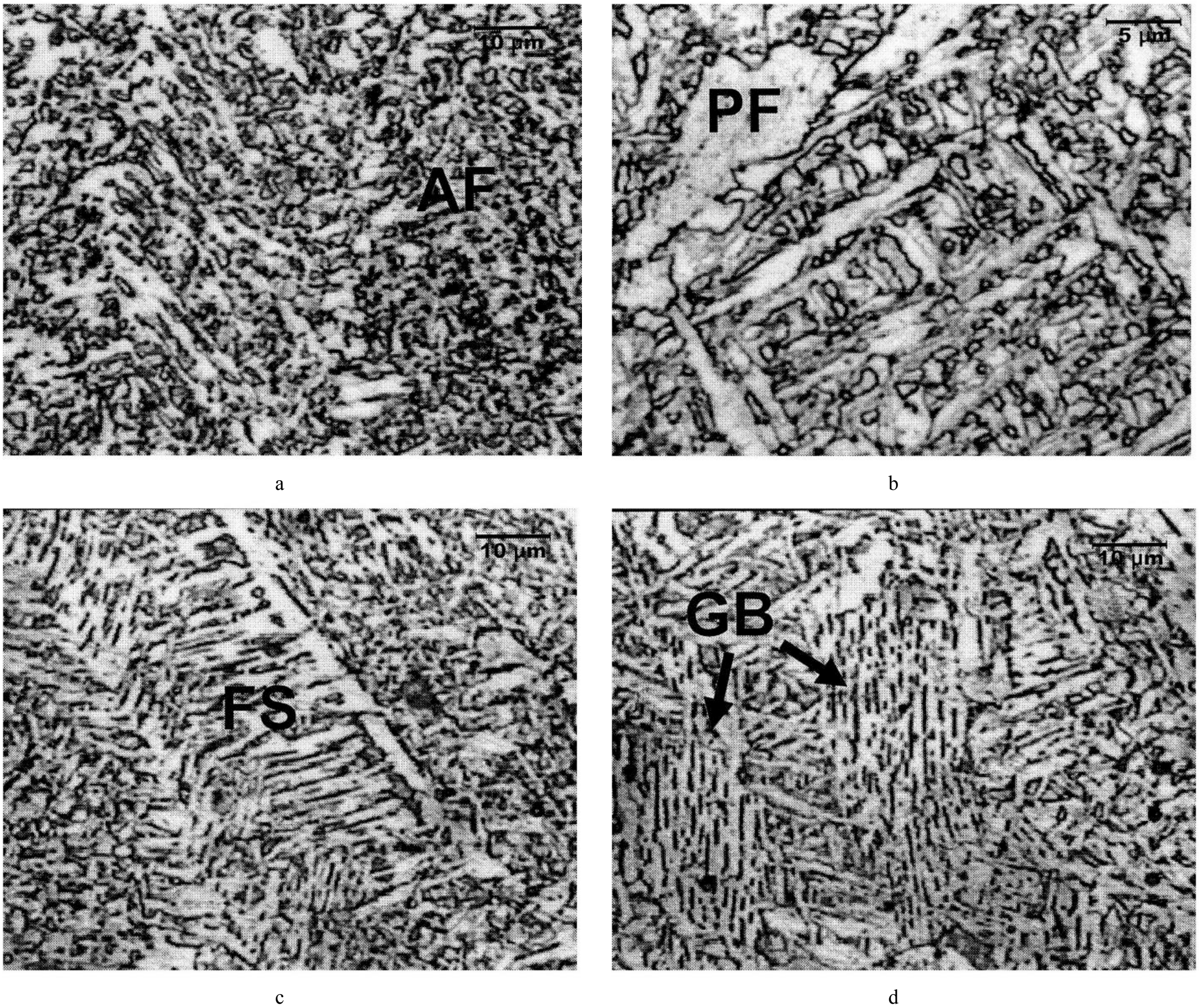

Fig. 1. Microstructure of: (a) acicular ferrite (AF); (b) proeutectoid ferrite (PF); (c) ferrite with secondary phase (FS); (d) upper bainite (GB).

Testing was performed on instrumented Charpy pendulum, at room temperature (20^{0}C), -40^{0}C and - 55^{0}C. On Figure 2 are shown: total impact energy ($\mathbf{E_u}$), crack initiation energy ($\mathbf{E_i}$), and crack propagation energy ($\mathbf{E_p}$), for these three temperatures. Crack initiation energy is not changing significantly with the temperature decrease, while on the other hand, the crack propagation energy is drastically decreasing with a temperature drop. Small values of crack initiation energy indicate that the crack development is evolving to complete fracture with low energy consumption. Since the possibility of crack appearance in weld metal must not be excluded, it is recommended that in the process of preparation of responsible welded structures crack initiation energy should be higher than the crack initiation energy at a given temperature. Considering the fact that in low-carbon low-alloy steel transition from ductile to brittle state takes place in a wider temperature range, we are coming to question which temperature range should be regarded as critical. There are some recommendations that this temperature for microalloyed steel is the one at which the minimum value of the toughness is 40J by K.Gerić et al. (1997).

Based on previously mentioned facts, it is logical that for reliable functioning of welded structures should be adopted the crack initiation energy higher than 40J, rather than total energy, because if there are cracks in welded joints, only the crack initiation energy matters. For considered case of welded joints in this paper, the crack growth energy at room temperature was 107J and it was bigger than the crack initiation energy (67J), which does not prejudice the reliability of welded joint. At the temperature of -40°C, the crack growth energy is significantly smaller than energy at room temperature (41J), and smaller than the crack initiation energy (56J) as well, so the reliability of the welded structure at this temperature is questionable. At the temperature of -55°C value of crack growth energy is 23J, so the production of welded structures at temperatures below -40°C is not recommended. This means that the criterion of the minimum of total impact energy is unreliable (in our case the total impact energy at -55°C is 70J), and the safety of the welded joint is provided only if minimum value of crack growth energy is adopted as acceptance criteria.

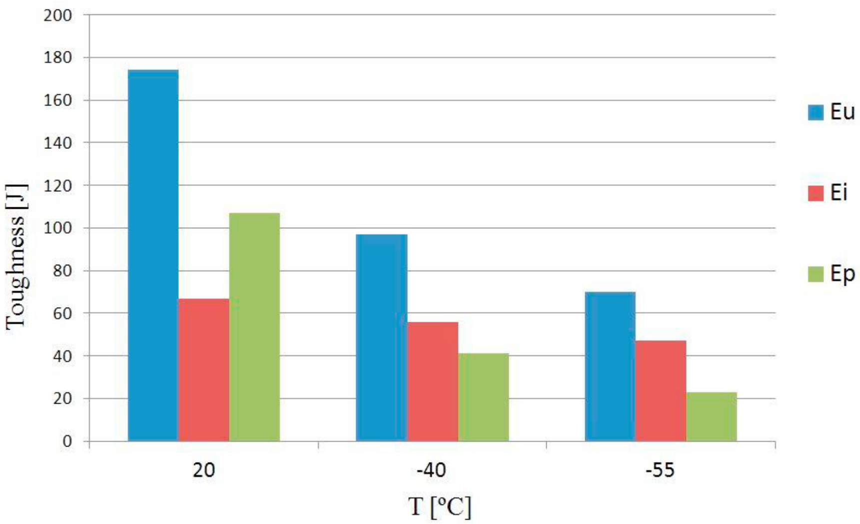

Fig. 2. Total impact energy (E_u), crack initiation energy (E_i), and crack propagation energy (E_p) as functions of temperature.

Diagrams force (F)-deflection (D_f), obtained by instrumented Charpy pendulum for testing temperatures are shown in Fig.3. Diagrams F-D_f , or area under the curve, represent the total impact energy needed for the failure of the specimen. In Figure 3 are shown the fractures on Charpy specimens at certain temperatures, as well as their fractography.

Analyzing the diagram F-D_f, as well as fracture surfaces, following facts can be observed:

- At room temperature there is not steep drop on the curve, which indicates the presence of ductile fracture. Fractographic analysis shows that at room temperature prevails ductile transgranular fracture, but small impact of brittle transgranular fracture exists as well. Ductile fracture is characterized by the presence of a large number of wells in which are noticed precipitates as possible initiators of decohesion of inclusions / base.
- At decreased temperatures reduces the total impact energy (area under the curve), in the diagram appears a steep fall, which indicates the presence of large share of the brittle fracture components. Fractographic analysis showed that at a temperature of -40°C brittle fracture occurs transgranularly with significant participation of inter-crystalline components of brittle fracture. Intergranular brittle failure occurs at a temperature when crack growth energy becomes lower than the crack initiation energy (Figure 2). This can be explained by the presence of a significant share of pro-eutectoid ferrite and ferrite with secondary phase at the borders of the original austenitic grains, which are characterized by low ductility by Z.Zhang et al. (1997) and C.B.Dallam et al. (1985).
- Share of components of the brittle fracture is increased with a decrease of temperature, and at a temperature of -50°C brittle fracture occurs transgranularly.

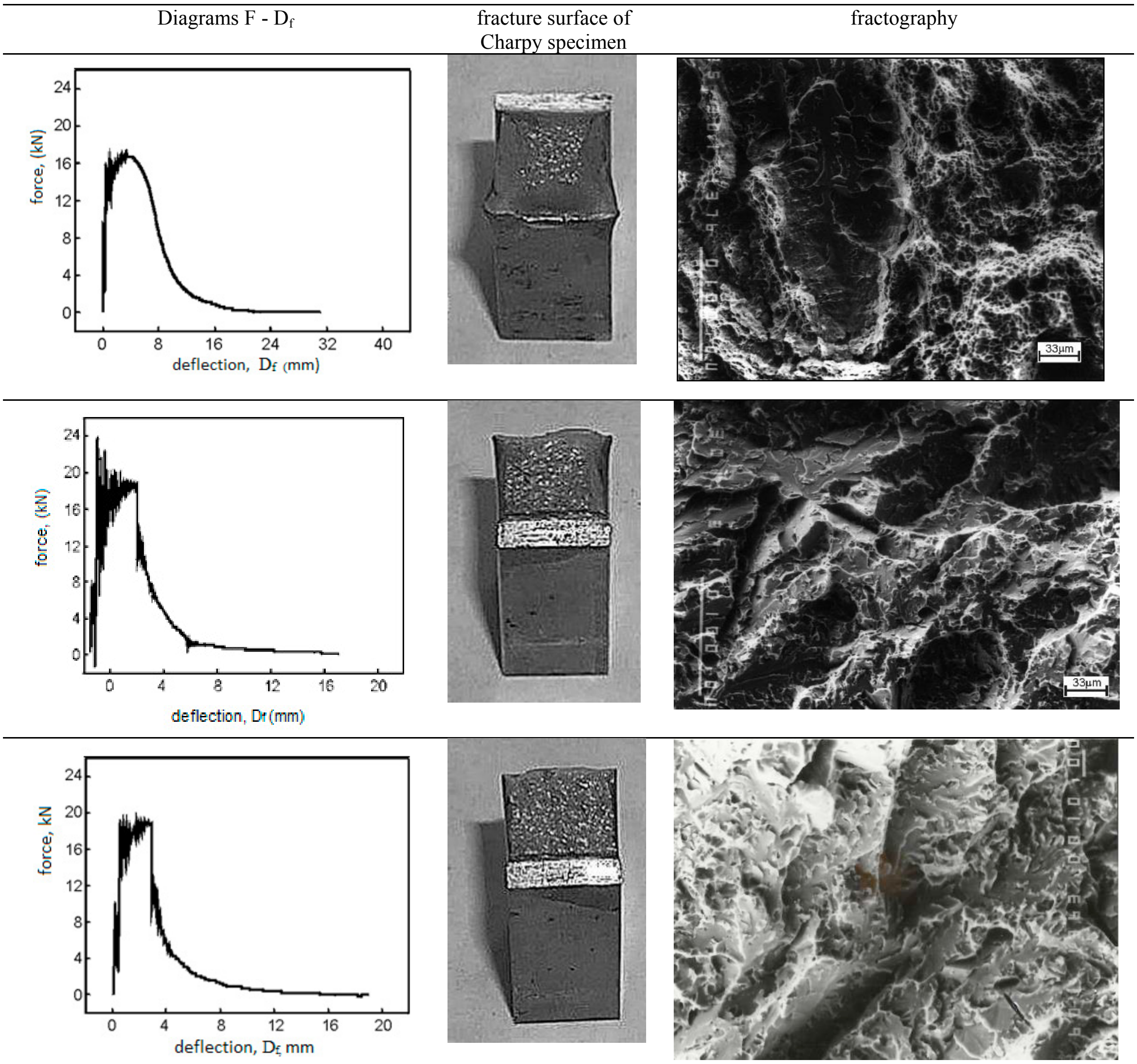

Fig. 3. Fracture analysis at 20^{0}C, -40^{0}C and -55^{0}C; diagram F-D_f; ; fracture surface of Charpy specimen; fractography.

4. Conclusion

Based on the analysis of experimental results, the following conclusions can be given:

- The microstructure of weld metal is composed of different morphological forms such as ferrite pro-eutectoid ferrite, ferrite and secondary phase and acicular ferrite. The presence of large acicular ferrite has a positive effect on toughness.
- At room temperature, crack growth energy is higher than crack initiation energy, while at -40^{0}C and -55°C is completely oposite, i.e., the crack initiation energy is higher than crack growth energy.
- With temperature decrease, the portion of brittle fracture increases, that is confirmed by diagram F- D_f.
- Fractographic investigation of the Charpy specimens indicates that at room temperature ductile transgranular fracture is dominant, with a small amount of brittle transgranular fracture. At the temperature of -40^{0}C brittle fracture occurs transgranularly, while at the temperature of -55°C, the share of brittle fracture is higher, and both transgranular and intergranular components of brittle fracture were observed.
- Intergranular brittle fracture becomes dominant when the propagation energy becomes smaller than the initiation energy.

Acknowledgements

The research was performed in the frame of the national project TR 35024 financed by Ministry of Science of the Republic of the Serbia.

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